Imaging Creep on the Hayward Fault System: Implications of Patterns and Transient Response for Earthquake Properties

External Grant Award 04HQGR0040

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Keywords: Fault stress interactions; Creep measurements; Seismotectonics

Investigations Undertaken

The role that fault creep plays in reducing the rate at which seismic moment accumulates on a fault to be later released during an earthquake is an important component of assessing the earthquake hazard on a fault. It is becoming a tractable parameter to analyze as better observations of fault creep are developed. However, unless a fault is creeping very near the surface, the effects of creep will be unlikely to be seen (or at least under-represented) in the local arrays, as these arrays typically span widths of less than 200 meters across the fault. Such “deep” creep will contribute to the overall pattern of crustal deformation along the fault, but it may not be an obvious signal in a sparse geodetic network. For such segments of the fault system, other information must be used to place constraints on the patterns of fault creep and the rates of slip deficit (and associated seismic moment) accumulation. Based on results from current research on the links between micro-seismicity and fault creep on the Hayward Fault (Malservisi et al., 2002), we believe we can improve the picture of fault creep along the Hayward, and its northern extensions, the Rodgers Creek and Ma’acama Faults.

Moving from the present-day pattern of fault creep (as observed and/or modeled) to an assessment of the pattern and magnitude of accumulated slip deficit on a fault also requires an understanding of the rates of creep, and how those rates have varied through time as a consequence of the earthquake cycle, and moderate/large magnitude regional earthquakes. Both observations and modeling indicate that earthquakes on and near the Hayward Fault perturb the pattern and rate of creep. Including this effect is clearly needed on the southern Hayward Fault and its transition to the Calaveras Fault where post-Loma Prieta effects have been seen. These effects will also have played an important role in the overall patterns of slip deficit accumulation on all of the fault strands after earthquakes on those (and nearby) segments.

In this project we couple detailed analyses of seismicity with observations of near-surface near-fault deformation and detailed 3-D deformational modeling to:

1. Map patterns of locked/creeping patches throughout the seismogenic layer on strike-slip faults in the San Francisco Bay region and north along the fault system.

2. Extrapolate observed creep/deformation through time, incorporating the transient and spatially varying effects of the past sequence of earthquakes and post-earthquake relaxation
3. Determine the pattern of accumulated slip deficit on the fault and evaluate potential seismic moment release on specific fault segments.

Results

The research completed under this award has resulted in several publications, on M.S. Thesis, and several abstracts of presentations at professional meetings. here we outline several of the key activities and outcomes.

In Figure 1 we show the model domain and its application to the San Francisco Bay area. The results that follow employed this model to assess the effects of locked and free-slip patches on the fault, the sensitivity of surface observations to these patches, and the transient response of creep on the fault to earthquakes. In this way we could assess the rate of unreleased moment accumulation throughout the earthquake cycle. The set of relocated earthquakes (Waldhauser and Ellsworth, 2002) used in this analysis is shown (map view) in Figure 2.

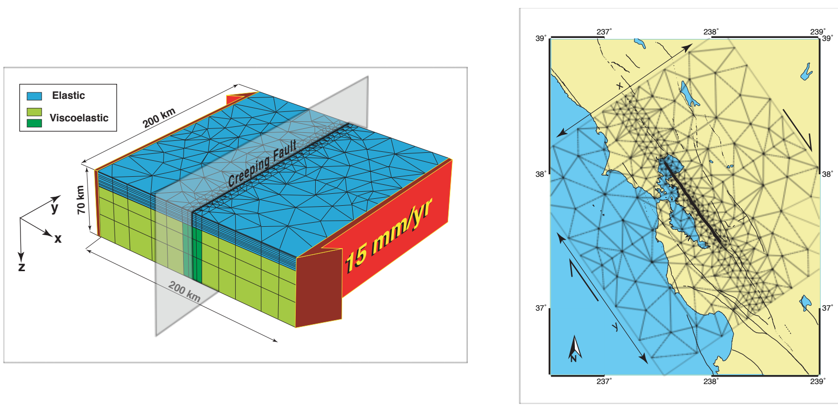


Figure 1. Model configuration for Hayward Fault modeling. The numerical Finite Element Model (FEM) incorporates visco-elastic rheologies and allows us to evaluate the conditions that drive creep on the fault, and the transient creep response after moderate earthquakes.

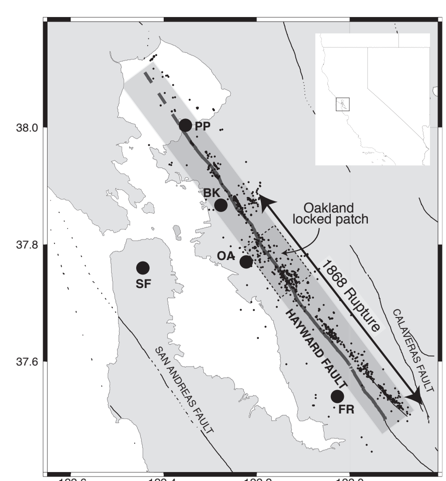


Figure 2. map view of relocated earthquakes (Waldhauser and Ellsworth, 2002) used in this study. Place names keyed to locations on other plots are shown: PP - Pinole Point, BK - Berkeley, OA - Oakland, FR - Fremont, and SF - San Francisco.

Results of this modeling include the following:

Micro-seismicity along the Hayward Fault falls into two categories that map into creep domains on the fault (Figure 3). Recurring or repeating earthquakes (earthquakes that regularly rupture the same small patch of the fault) almost exclusively occur on regions of the fault that otherwise exhibit substantial creep. This is in contrast to the background micro-seismicity that tends to occur dominantly in the transitions from locked patches to freely creeping patches (Malservisi et al., 2005).

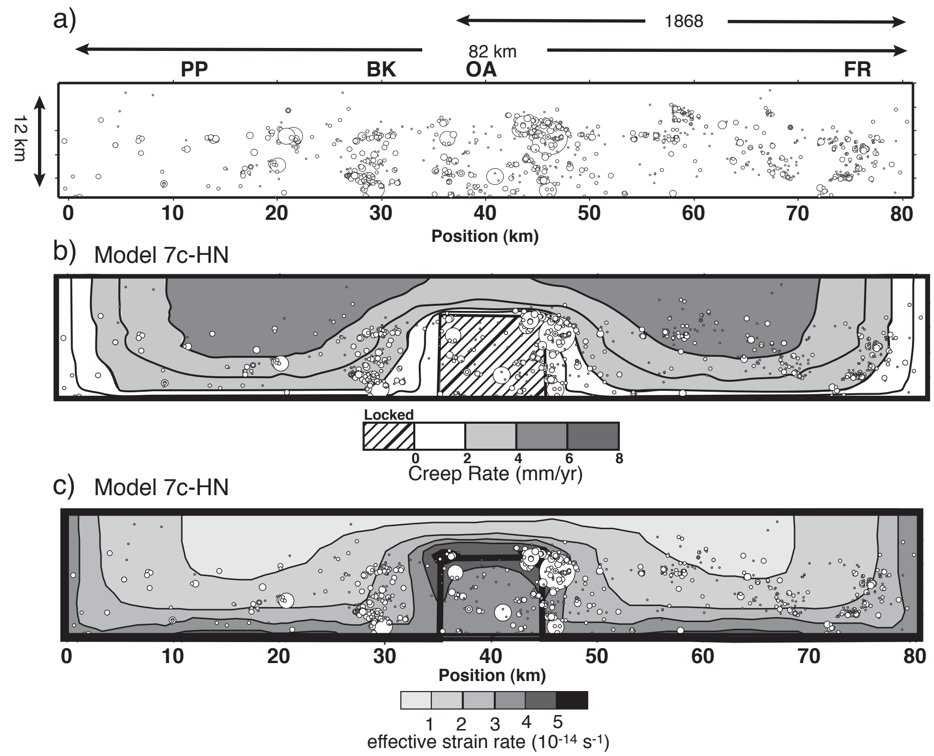


Figure 3. Comparison of Hayward Fault microseismicity (Waldhauser and Ellsworth, 2002) with model results for fault creep and effective strain rate. In upper figure all seismicity is shown. in comparison with model results only the non-recurring events are included.

The pattern of locked and creeping patches on the fault will perturb the stress field. When patterns of Coulomb stress are compared with both the spatial distribution of seismicity and the resulting expected focal mechanisms (Figure 4) we find a correlation with the observed micro-seismicity. In particular in the vicinity of locked patches, seismicity tends to occur over a broader region (away from the fault). Additionally the orientations seen in focal mechanisms also rotate in the vicinity of locked patches (Malservisi et al., 2005)

In addition we have analyzed the effects of moderate earthquakes in producing transient patterns of creep on the fault (Figure 5). For a simple 1-meter slip event on the locked patch beneath Oakland, the creep rate on the fault increases and remains high for >50 years. Even after the slip in the near-surface has returned to pre-earthquake levels, creep rates at depth continue to remain elevated (Malservisi et al., 2005). We have also tested the effects of a more complex pattern of earthquake slip (compatible with a model of moment accumulation derived from current creep patterns) (Figure 6). In this modeling we find that during the first 30-40 years after the earthquake, details of the co-seismic slip distribution affect the pattern of creep rate increase (Gans, 2004).

Figure 4. Modeled Coulomb Stress compared to distribution of seismicity and effect on focal mechanisms. Cross-sections indicate a broadening of the region of stress perturbation in association with locked patches.

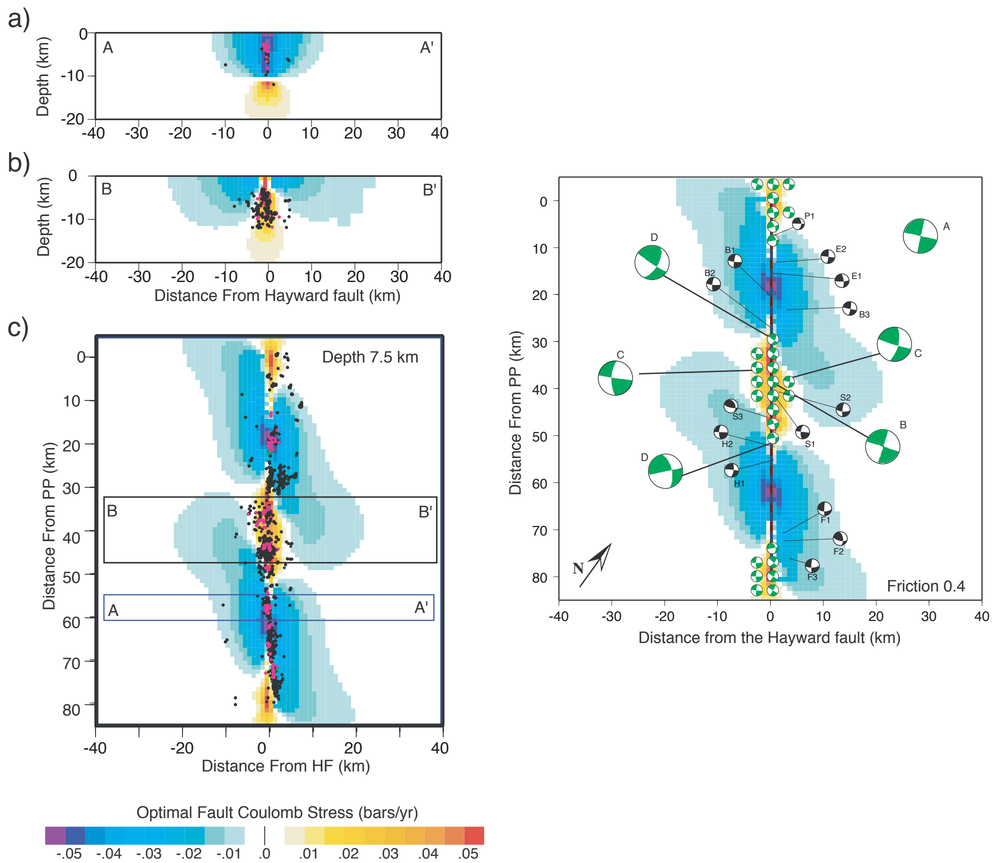
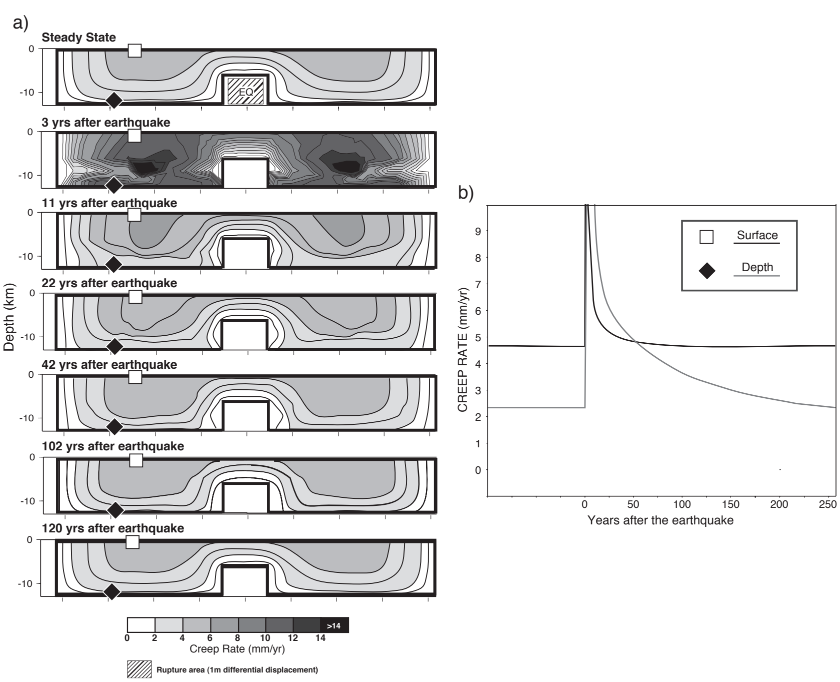


Figure 5. Patterns of fault creep in response to a simulated moderate earthquake (1-meter slip) on the 'Oakland' locked patch (square locked patch in the center of the model). Fault creep is transiently increased, with rates returning to background levels at shallow levels prior to those at depth.



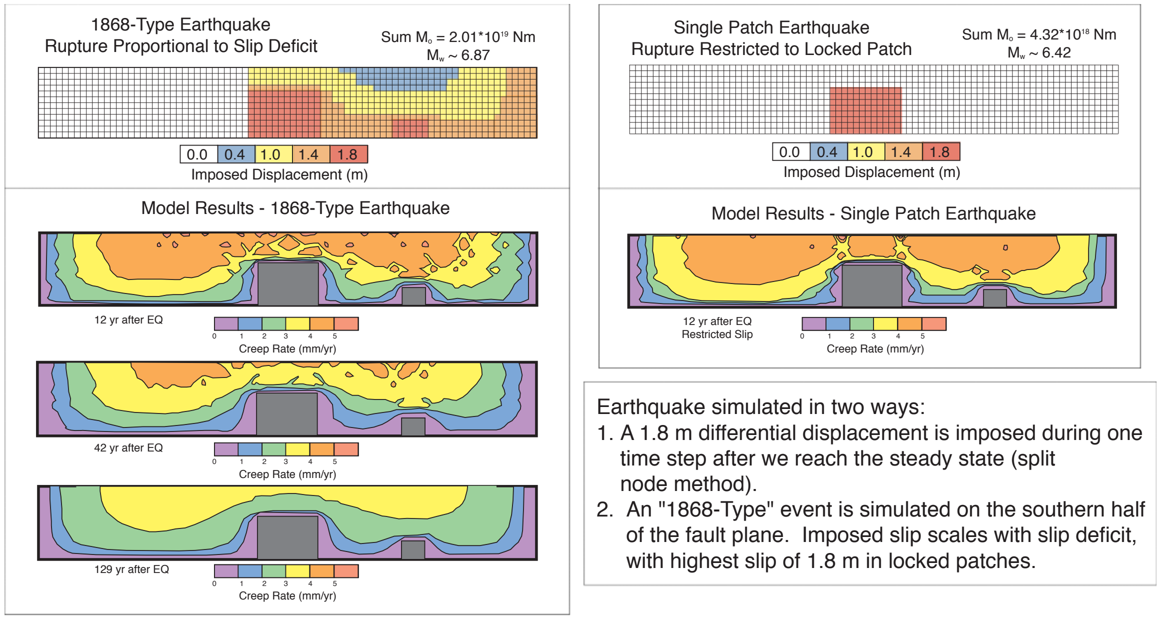


Figure 6. Transient fault creep for models with various patterns of co-seismic slip.

As part of this project we are also completing a relocation of seismicity on the Rodgers Creek - Ma'acama Fault system. In the original funding of this project it was indicated that this work would be accomplished by others. Those results are not yet available so we are undertaking our own relative relocation exercise (using the techniques of Waldhauser and Ellsworth, 2002). Initial results of this research is shown in Figure 7. Of particular importance is a SW-NE trending swath of seismicity that links to the northern Hayward Fault in San Pablo Bay in the vicinity of the fault step-over to the Rodgers Creek Fault. Some of the shallow seismicity in this relocated band of seismicity is associated with surface mining, but the deeper events are clearly earthquakes (well recorded S-waves) and indicate additional complexity in the San Andreas Fault system in the northern San Francisco Bay region.

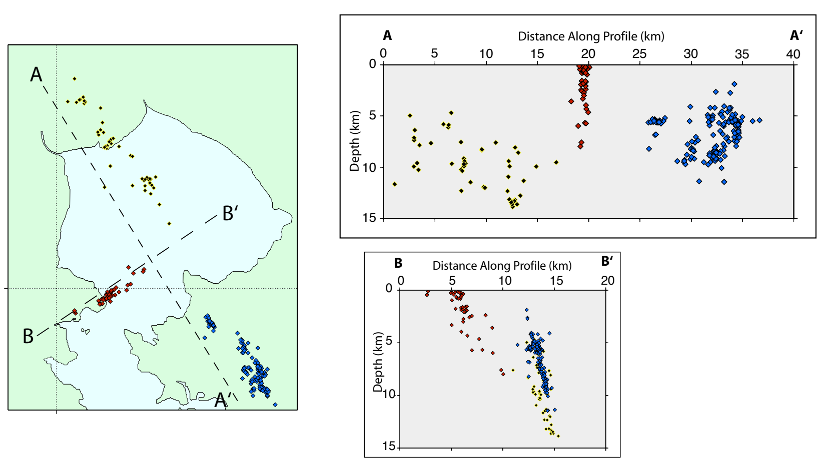


Figure 7. Relocated seismicity in the northern San Francisco Bay - San Pablo Bay region. Of particular importance is the SW-NE trending seismicity that links with the Hayward - Rodgers Creek Faults in the vicinity of the fault stepover.

Non-Technical Summary

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The patterns of aseismic creep on a fault provides information on the physical properties of the fault surface. By coupling surface observations of fault creep with patterns of seismicity on the fault, we have obtained improved images of the subsurface pattern of fault creep and the distribution of locked and creeping patches on the fault. In response to a moderate sized earthquake on the fault, creep is accelerated for a period of approximately 50 years. This both reduces the rate at which seismic moment accumulates on the fault and affects the pattern of maximum moment release during subsequent earthquakes.

Reports Published

Papers:

Malservisi, R., K.P. Furlong, C.R. Gans, 2005, Using Microseismicity to Map Creep on a Fault Plane: Hints from Modeling the Hayward Fault, California (USA) Earth Planet Sci Lett doi: 10.1016/j.epsl.2005.02.039

Furlong, Kevin P., and Susan Y. Schwartz, 2004, Influence of the Mendocino Triple junction on the tectonics of Coastal California, Ann Rev. Earth Planet. Sci., 32, pp. 403 – 433, doi: 10.1146/annurev.earth.32.101802.120252

Gans, C.R., K.P. Furlong, and R. Malservisi, Implications of Earthquake-induced Transient Fault Creep for the Earthquake Potential of the Hayward Fault (in preparation)

Theses:

Gans, Christine R., 2004, Investigations of Strike-slip Plate Boundaries: Numerical Modeling of Creeping Faults in Central California, and Spatial and Temporal Slip Distribution in Southern California (85 pp.) M.S. Thesis in Geosciences, Pennsylvania State University, University Park, PA

Abstracts:

Malservisi, R.; Gans, C.R.; Furlong, K.P., Using microseismicity to help to map creep on a fault plane: hints from modeling the Hayward fault, Abs. papers presented at the 1st EGU Congress (EGU04-A-03931)

Johnson, C B, K.P. Furlong, E. Kirby, Possible Geometry and Implications for Potential Blind thrusts Beneath the Marin County – Mt Tamalpais Region, Eos Trans. AGU, 85(47), Fall Meet. Suppl., Abstract T41F-1283.

Furlong, K.P., E Kirby, Potential for Blind Thrust(s) Beneath the Marin County – Mt Tamalpais region, Eos Trans. AGU, 85(47), Fall Meet. Suppl., Abstract T42B-04.